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μ PROBLEM, SO(10) SUSY GUT AND HEAVY GLUINO LSP[*†]

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We present a solution to the μ problem in an SO(10) supersymmetric grand unified (SUSY GUT) model with gauge mediated (GMSB) and D-term supersymmetry breaking. A Peccei-Quinn (**PQ**) symmetry is broken at the messenger scale and enables the generation of the μ term. The invisible axion (Goldstone boson of **PQ** symmetry breaking) is a cold dark matter candidate. At low energy, our model leads to a phenomenologically acceptable version of the minimal supersymmetric standard model (MSSM) with novel particle phenomenology. Either the gluino or the gravitino is the lightest supersymmetric particle (LSP). The phenomenological constraints on the model result in a Higgs with mass $\sim 86 - 91$ GeV and $\tan\beta \sim 9 - 14$.

MSSM is a strongly motivated candidate for the physics beyond the Standard Model (SM). There are two Higgs doublets (H_u and H_d) in the MSSM. The vacuum condition obtained by minimizing the tree level Higgs potential at the electroweak (EW) scale is

$$\mu^2 = -\frac{M_Z^2}{2} + \frac{m_{H_d}^2 - m_{H_u}^2 tan^2\beta}{tan^2\beta - 1}, \tag{1}$$

where $\tan\beta = \langle H_u\rangle/\langle H_d\rangle$, $m_{H_u}^2(m_{H_d}^2)$ is the SSB mass of $H_u(H_d)$ and B is the SSB Higgs bilinear coupling. On the left hand side of Eq. 1, the μ parameter, multiplying a supersymmetric μ term in the Lagrangian, breaks no SM symmetries; it could in principle be as large as the Planck or GUT scales. On the right side, the Z boson mass and the SSB Higgs masses are of order the EW scale as required to solve the hierarchy problem in the SM. To avoid fine tuning in Eq. 1, the μ parameter should also be of order the EW scale. The μ problem [1] is stated as the difficulty to generate a μ parameter which is naturally of order the EW scale.

In this paper we use an extension of the GMSB model discussed in Ref. [2] to solve the μ problem. This model has GMSB with Higgs-messenger mixing in an SO(10) theory and naturally leads to a stable gluino with mass in the range $25 - 35$ GeV. Such gluino is still allowed by both the CDF and LEP data [3,4] and is a candidate for the ultra high energy cosmic rays (UHECRon). Either the gluino or the gravitino is the LSP in this model. In the case of a gravitino LSP, gluino lives long enough (one month) to be considered stable for both CDF-LEP and UHECRon analyses.

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*This talk is based on the work done in collaboration with S. Raby. The interested reader is referred to our paper [1] for a more detailed discussion of the model and its phenomenological implications.
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The theory at the GUT scale is defined by the SO(10) invariant superpotential $W \supset W_1 + W_2 + W_3$ and a non-renormalizable term in the Kahler potential K where

$$
\begin{aligned}
W_1 &= \mathbf{16}_3\mathbf{10}_H\mathbf{16}_3, \qquad & W_2 &= \mathbf{10}_H A \mathbf{10}_A + X\mathbf{10}_A^2, \\
W_3 &= \bar{\eta}_1 A \eta_1 + \bar{\eta}_2 A \eta_2 + \bar{\eta}_1 \eta_2, \qquad & K &\supset \lambda_K \tfrac{X^\dagger}{M_P}\mathbf{10}_H^2 + h.c.
\end{aligned}
\tag{2}
$$

($\mathbf{16}_3,\ \eta_1,\ \eta_2$) are $\mathbf{16}$'s, ($\bar{\eta}_1,\ \bar{\eta}_2$) are $\bar{\mathbf{16}}$'s, ($\mathbf{10}_H,\ \mathbf{10}_A$) are $\mathbf{10}$'s, (X) is a singlet and (A) is an adjoint under SO(10).

At the GUT scale, the theory is invariant under a U(1) **PQ** and an R symmetry. The R symmetry is broken spontaneously at the GUT scale. The **PQ** symmetry, however, is not broken at the GUT scale and prevents a μ term in the superpotential.

W_1 contains the coupling of the third family matter multiplet ($\mathbf{16}_3$) to the Higgs field ($\mathbf{10}_H$) which includes both the weak doublet and color triplet Higgs fields.

W_2 provides doublet-triplet splitting using the Dimopoulos-Wilczek mechanism in order to avoid rapid proton decay [5]. The adjoint field A gets a vev $\langle A \rangle = (B-L)M_G$ where $B-L$ (baryon number minus lepton number) is non-vanishing on color triplets and zero on weak doublets. The singlet X gets a vev $\langle X \rangle = M + \theta^2 F_X$. This gives mass of order M_G to the color triplet Higgs states and of order M to the weak doublets in $\mathbf{10}_A$. The Higgs doublets in $\mathbf{10}_H$ remain massless. A SUSY breaking vev is also contained in W_2.

W_2 and W_3 provide the messengers for SUSY breaking.‡The auxiliary field $\mathbf{10}_A$ and the fields $\bar{\eta}_1, \eta_2$ feel SUSY breaking at tree level due to the vev F_X. They are thus the messengers for GMSB. We take the messenger scale $M \sim 10^{12}$ GeV with the effective SUSY breaking scale in the observable sector given by $\Lambda = F_X/M \sim 10^5\ GeV$.

When X gets a vev, both SUSY and the **PQ** symmetry are broken. The μ term is generated at the scale M, $\mu = \lambda_K \frac{F_X}{M_P}$, while B remains zero at tree level §

The **PQ** symmetry solves the strong CP problem and produces an axion; the Goldstone boson of the broken **PQ** symmetry. Such axion is a candidate for the cold dark matter.

The boundary conditions at the messenger scale are determined by two sources of SUSY breaking, gauge mediation and D-term [1,2]. The messengers give mass to the gauginos and Higgs at one loop and to squarks and sleptons at two loops. Since the color triplet messengers have mass of order the GUT scale, the gluino mass is suppressed compared to the other gauginos. For phenomenological reasons we assume that SUSY is also broken by the D-term of an anomalous $U(1)_X$ gauge symmetry [1,2]. Moreover, the GMSB and D-term contributions are necessarily comparable [6]. The D-term contribution to scalar masses is given by $\delta_D \tilde{m}_a^2 = d\, Q_a^X\ M_2^2$, where Q_a^X is the $U(1)_X$ charge of the field a and d is an arbitrary parameter of order

‡Due to an accidental cancellation, gluinos receive no mass at one loop from W_2. Thus W_3 is introduced with additional messenger fields ($\eta_1, \bar{\eta}_1, \eta_2, \bar{\eta}_2$) contributing to the masses of gauginos and scalars at the scale M_G.

§It is necessary to generate B at higher loop orders than μ to avoid a B hierarchy problem.

1 which measures the strength of D-term versus gauge-mediated SUSY breaking. The value of Q_a^X for $a = \mathbf{16},\ \mathbf{10},\ \mathbf{1}$ of SO(10) is given by $1,\ -2,\ 4$ [1,2].

Imposing gauge coupling unification at the GUT scale, we renormalize the effective Lagrangian parameters to the EWSB scale and determine the free parameters of our model by fitting the low energy data which we take to include $m_t,\ m_b,\ m_\tau,\ \alpha_{em},\ \alpha_s$ and $\sin^2\theta_W$.

We now consider the LEP constraints on parameters in our model. The most important constraints come from the latest Higgs search results at LEP [7]. In our model the off-diagonal elements in the stop mass-squared matrix are very small, thus the severe LEP limits for the neutral Higgs in the no stop-quark mixing scenario are most applicable [7]. In our model only $d \sim\ 0.40 - 0.45$ survives the LEP constraint for $\Lambda = 10^5$ GeV. With these values of the parameters, the mass of the lightest neutral Higgs resides in the narrow range $\sim 86 - 91$ GeV with $\tan\beta \sim 9 - 14$. For $d \sim\ 0.40 - 0.45$ and $\Lambda = 10^5$ GeV we find the lightest stop and neutralino with mass in the range 100 - 122 GeV and 50 - 72 GeV, respectively.[¶]

Our model survives the OPAL limit on $e^+\ e^- \to$ hadrons coming from chargino and neutralino pair production. We have also analyzed the one loop branching ratio for $b \to s\gamma$. We suggest that in the desired region of parameter space, our model is not excluded by CLEO data.

To summarize, we have presented a solution to the μ and strong CP problems in the presence of a heavy gluino LSP. Either the gluino or the gravitino is the LSP. A light gluino reduces the fine tuning necessary for EWSB and is a candidate for the UHECRon. It also leads to a model with Higgs mass of order 90 GeV and a stop mass less than the top satisfying some of the dynamical constraints necessary for electroweak baryogenesis in supersymmetric theories. The axion; the Goldstone boson of the **PQ** symmetry is also a candidate for the cold dark matter.

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¶Note, a recent LEP bound on a heavy gluino LSP using stop production and decay [8] does not constrain the model since the stop mass in our case is larger than the values probed in this search.